Strained Germanium Nanostructures on Silicon Emitting at >2.2 μm Wavelength

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***Abstract*—The photoluminescence of process-induced tensile strained nanostructures fabricated using Ge on Si is reported. 100 nm pillars were etched and embedded in a silicon nitride thin film demonstrating photoluminescence emission up to ~2.5 μm.**

I. Introduction

Germanium has regained interest for applications in both electronics [1] and photonics [2] due to the suitable intrinsic properties that include high mobility, a band edge at 1.6 μm, low absorption in the mid-IR and also by the progress delivered by the maturing growth technology. Recent work has demonstrated both optically pumped [3] and electrically pumped Ge lasers [4] potentially opening the route towards an integrated Ge laser source on Si substrates. Two keys elements for producing sufficient gain for a Ge laser are a high level of n-doping (to move the Fermi level into the Γ-valley) and a high level of tensile strain in the material (which reduces the energy between the Γ-valley and the L-valley) [5], [6], [7]. This paper demonstrates a technique to strain Ge nanostructures to high levels of strain that significantly reduce the bandgap to a level that common deformation potentials [8] suggest is direct bandgap.

II. Fabrication

650 nm strain relaxed virtual substrates of undoped Ge were directly grown onto a 200 mm p$^-$-Si (001) wafer by an ASM Epsilon 2000E CVD tool using the method described in [9]. Two different wafers were grown, one doped and one undoped. For the doped wafer, 300 nm of n-Ge with $N_D \approx 3 \times 10^{19}$ cm^{-3} phosphorus was grown at 450 ^{o}C. The activated density was obtained by electrical measurements on Hallbars at 300 K. Once cooled to 293 K, the n-Ge possesses ~0.25 % of tensile strain as measured by photoluminescence. The same growth process and layer thicknesses were used for the undoped material.

Bulk devices consisting of 300 μm wide mesas were produced from the material by dry etching mesas of ~1 μm depth and using NiGe Ohmic contacts [10] to produce LEDs. For the highly strained devices, electron-beam lithography was used to define 100 nm dots in HSQ resist before a low-damage dry etch process [11] was used to define pillars. High aspect ratio nanostructure pillars of over 1:10 aspect ratio were produced as shown by the scanning electron microscope (SEM) image of Fig. 1. In order to stress such structures a thin film of 500 nm thick Si_3N_4 was deposited using a PECVD tool. By changing the parameters of deposition the stress in the Ge nanostructures could be varied between 2 to -3 GPa (the sign defining compressive (<0) and tensile (>0) stress).

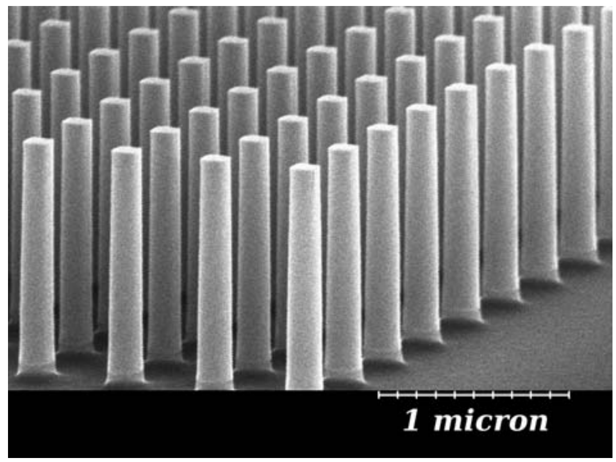

Fig. 1. A SEM picture of an array of pillars (100 nm width) etched down 1 μm deep before the deposition of silicon nitride.

III. Characterisation

The structures were characterised optically using either an electroluminescence (EL) or a photoluminescence (PL) set-up with a Bruker Vertex 80 Fourier Transform Infrared Spectrometer (FTIR). A solid-state green laser (532 nm) source was focused onto the structures to for characterization with a penetration depth on the doped material of ~18 nm. A cooled InGaAs detector with a cut-off filter of ~2.5 μm was used for detection. All measurements were undertaken in step-scan mode to

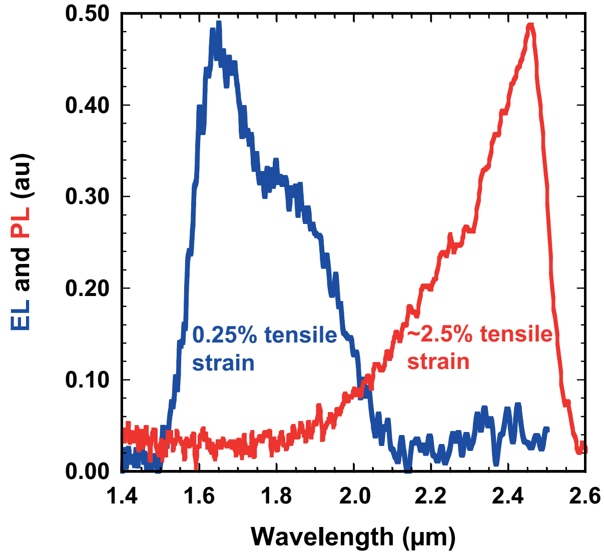

Fig. 2. Left: EL spectra of an LED fabricated from the as grown Ge on Si heterolayer which has approximately 0.25 % tensile strain. Right: PL spectra of an array of pillar 100 nm in diameter covered with 500 nm compressive Si_3N_4 which produces approximately 2.5% tensile strain at 300 K.

reduce heating and to improve the signal to noise ratio. The estimated optical power density at the surface of the Ge was below 1 kW/cm^2 for CW illumination.

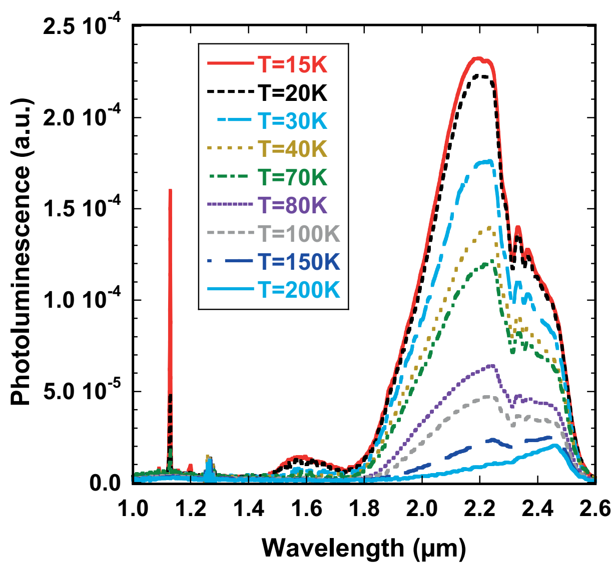

Fig. 3. The PL spectra of an array of pillar 100 nm in diameter covered with 500 nm compressive Si_3N_4 at different temperatures. The sharp PL is the Si exciton. The detector cut-off is $\sim$2.5 μm.

Fig. 2 demonstrates the El emission from the as grown Ge heterolayer with $\sim$0.25 % tensile strain and the PL emission from an array of pillars covered with 500 nm of Si_3N_4 (both in step-scan mode).The PL spectra were also obtained at different temperatures ranging from 15 K to 200 K as shown in Fig. 3. The integrated PL intensity increases exponential increase as the temperature is decreased. The spectra are complicated by the detector cut-off, optical interference effects and the associated role-off to $\sim$2.5 μm but demonstrate a movement of the PL emission to longer wavelength at higher temperatures. Comparison with calculations from deformation potentials [8] suggest the material may be direct bandgap at this level of tensile strain. Further experiments are required to demonstrate if stimulated emission can be achieved in undoped material to demonstrate if this material is definitely direct bandgap Ge.

IV. Conclusions

Process induced strain on 100 nm diameter Ge pillars has demonstrated PL emission out to $\sim$2.5 μm wavelength. We believe that this work potentially opens the route towards a direct bandgap Ge on Si laser at wavelengths above 2.2 μm.

V. Acknowledgements

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